# State of the art & future developments in the detection of nuclear/radioactive materials

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# Overview

**Definition of needs**

**State-of-the-art**

**Capability gaps**

**R&D requirements**

**The goal of detection measures is to reveal the presence of:**

**WHAT?**

- **Radioactive Sources**
- **Special Nuclear Material**

**WHERE?**

- **Concealed in transports**
- **Borne by people**
- **Left in public places**

**WHY? To prevent:**

- **Preparation/use of an IND (crude nuclear weapon)**
- **Preparation/use of a RDD (dirty bomb)**
- **Contamination of public places, distribution networks, critical infrastructures,…**

**Materials to be detected:**

- **Fissile materials (U and Pu)**
- **Other radioactive materials**

**Detection principle: radiation**

**Detectable types of radiation:**

- **Photons**
- **Neutrons (Pu only)**

# Detection principles



**The ideal detector should have/be:**

- **High sensitivity and efficiency**
- **Capability to discriminate the radiation source**
- **Easy to use (for non-experts)**
- **Reliable and able to work in harsh environmental conditions**

**Radiation detection:**

**RS/SNM can be revealed by detecting the radiation they emit**

**Only exploitable radiation types: Photons / Neutrons**

**Main factors playing a role in radiation detection:**

- **Amount and quality of radiation**
- **Properties of the sensor (efficiency/sensitivity/selectivity)**
- **Distance source/detector**
- **Exposure time**
- **Presence of radiation (background/natural/other sources)**
- **Presence of shields**

# Efficiency (requirements)



**High efficiency is required in order to maximise the probability that the detector "sees" the radiation:**

- **Geometry effect:** **the larger is the detector surface, the larger will be the solid angle covered, so the probability that the radiation will reach the detector**
- **Interaction probability:** **proportional to thickness and density of the detection material**

**Simplifying: efficiency increases with detector volume**

# Efficiency (state-of-the-art)



**Current technology in radiation detection (efficiency):**

| Detector family | Surface | Volume |
|---|---|---|
| Liquid scintillators | Any | Any |
| Plastic scintillators (PVT) | ~$10^4$ $cm^2$ | ~$10^1$ l |
| Inorganic scintillators (NaI, $LaBr_3$,…) | ~$10^2$ $cm^2$ | ~$10^0$ l |
| Semiconductors (HPGe,…) | ~$10^1$ $cm^2$ | ~$10^{-1}$ l |

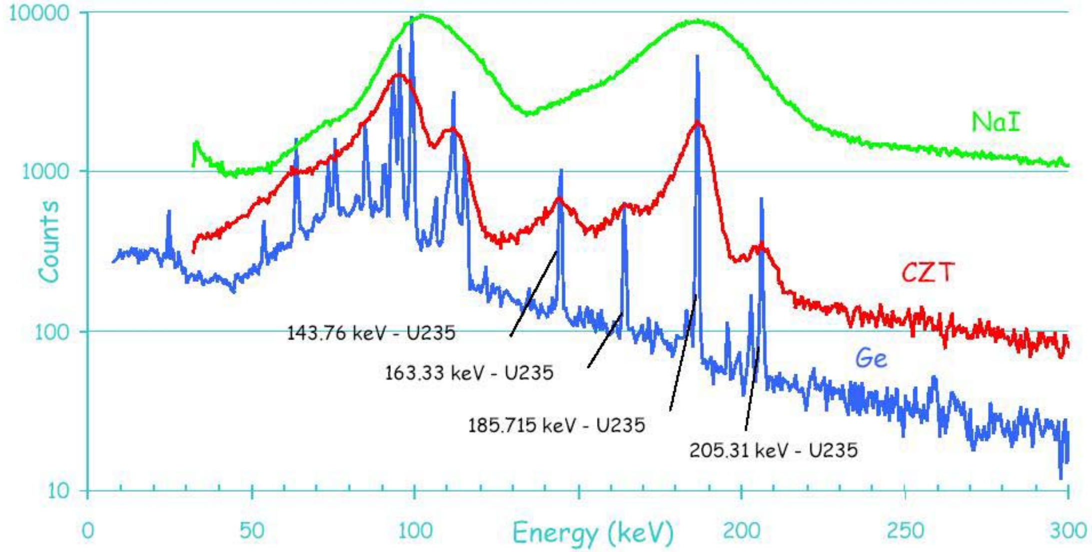
# Resolution (requirement)



**Resolution is required in order to discriminate and identify the material that has emitted the radiation**

**When a detector measures not only the presence of radiation (counting), but also is able to quantify the energy of the emitted photon (spectroscopy) it is possible to determine the isotope that has generated it**

**Resolution is the precision with which the photon energy is measured that determines the capability to isolate a characteristic peak in a spectrum**



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# Resolution (state-of-the-art)



## Current technology in radiation detection (resolution):

| Detector family | Resolution | Capability |
|---|---|---|
| Liquid scintillators | No | No discrim. |
| Plastic scintillators (PVT) | Poor | Categorisation |
| Inorganic scintillators (NaI, $LaBr_3$,…) | Good | Simple spectra |
| Semiconductors (HPGe,…) | Excellent | Complex spectra |

# Detectors (state-of-the-art)

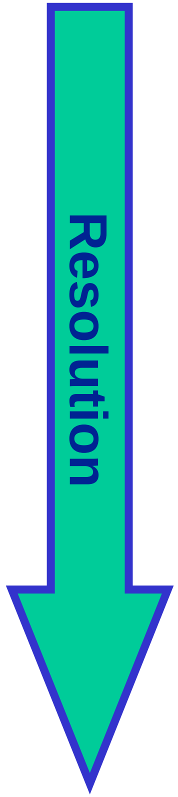



**Liquid scintillators**

**Plastic scintillators (PVT)**

**Inorganic scintillators (NaI, $LaBr_3$,…)**

**Semiconductors (HPGe,…)**




**No perfect solution !**

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# The process



| | |
|---|---|
| Detection | Is there something? YES/NO |
| Radiation Hazard Assessment | Is there radiation hazard? YES/NO |
| Localization | Where is it? |
| Categorization | What is it? SNM – IND – MED - NORM |
| Characterization | Composition and mass |
| Forensic Investigation | Where it comes from? Which purpose? |

Protect yourself from possible radioactive contamination by observing standard precautions (**personal protection equipment**).

**Preserve the evidences** that are present on the scene.

# The process



| | |
|---|---|
| Detection | Fixed installations (Radiation Portal Monitors) |
| Radiation Hazard Assessment | Personnel and Contamination Monitors |
| Localization | Hand-held devices |
| Categorization | Hand-held devices |
| Characterization | Laboratory Equipment |
| Forensic Investigation | Specialized Laboratory |

# The process



- Detection
- Radiation Hazard Assessment
- Localization
- Categorization
- Characterization
- Forensic Investigation


# A complete tool kit

| Instruments | Function |
|---|---|
| Portal monitors | Detection / alarm trigger |
| Hand-held radiation monitors | Source localisation |
| Portable gamma spectrometers | Gamma emitter identification |
| Portable neutron detectors | Neutron emitter detection |
| Contamination monitors | Check surface contamination |
| Personal pagers | Monitor personnel exposure |

# Portal monitors



High efficiency/low resolution detectors:

- Photons: PVT based plastic scintillator
- Neutrons: He-3 tubes moderated with polyethylene

Used for:

- Persons
- Baggage
- Vehicles (car, truck, train)
- Containers

Distance between 2 vehicles detectors: a few meters (~3 to 6), speed: 8km/h

Distance for pedestrian detector 1m, speed:1.2m/s (normal walking speed)

# Hand-held radiation monitors



- Radiameters
- Probes



# Hand-held spectrometers



Gamma spectrometers (NaI(Tl) scintillator, HPGe or CdZnTe) allow nuclide identification

Energy Range 0.05 to 3 MeV

Minimum performance recommendation: at a mean indication of 0.2mSv/h an alarm should be triggered for an increase dose rate of 0.05mSv/h for 1s


# Portable neutron detectors



Detector neutrons: He-3 tubes moderated with polyethylene


Minimum performance recommendation: alarm should be triggered when exposed to a Cf-252 source of 0.01 mg (~20000n/s) for 10s at 0.25 m when shielded to less than 1%

Neutron detection is a signature for possible presence of plutonium

# Contamination monitors



Detection of alpha contamination necessary for handling procedure

# Personnel monitors (pagers)

Small equipment to be worn by personnel with dosimeter and acoustic alarm




# Detectors (state-of-the-art)

**For reaction at borders a two-step procedure is applied:**

**I – Alarm triggered by a high efficiency fixed portal monitor (RPM)**


**II – Secondary inspection done by the front-line officer using portable equipment**

# Radiation Portal Monitors



- **RPM: Radiation Portal Monitor installed at border checkpoints (road, rail, airport, seaport) to detect the presence of smuggled nuclear and other radioactive materials**


Vehicles at
land border crossings


Containerized Cargo
at seaports


Rail crossing


Pedestrian crossing

- **Their main requirement is a high efficiency: detect the presence of radioactive material in the short transit time**

# Radiation Portal Monitors

- **RPM are therefore based on material having the possibility to be built in large dimensions (plastic scintillators)**

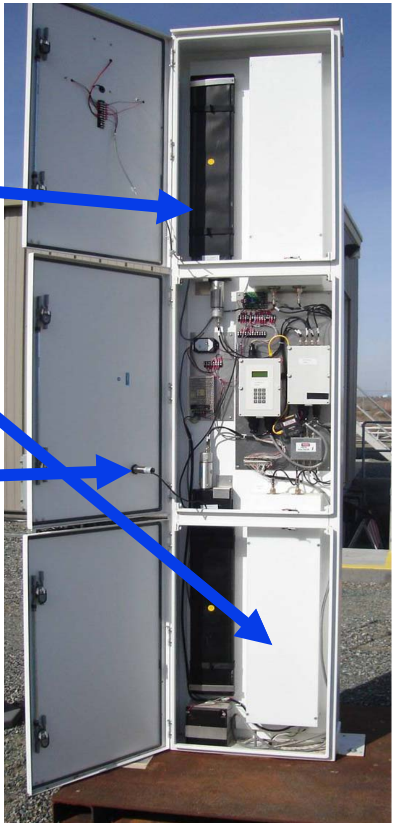

- **The problem: Plastic scintillators have a high efficiency, but an extremely poor resolution. This means that it is not possible determine the energy of the radiation and therefore they cannot identify the isotope originating the radiation**

# Radiation Portal Monitors



**This equipment does not emit radiation, it only detects radiation**

- Gamma radiation detectors (plastic scintillators wrapped in black paper/tape)
- Neutron detectors (He-3 gas tubes in PE box)
- Occupancy Sensors detect presence of people, vehicles or containers between portal, based on ultrasonic, radar or infrared
- Battery Backup
- Possible RPM Alarms: neutron, gamma, combined gamma-neutron, tamper, high / low background, internal fault



## Strengths

- Plastic scintillators can be made in relatively large size
- They have quite a large efficiency in gamma detection
- They can be integrated in the same case with $^{3}$He neutron detectors
- They can detect small amounts of R/N material in a very short time
- They are not intrusive wrt vehicle throughput at border
- They are not very sensitive to environmental conditions
- Relatively cheap (wide market)

## BUT

Plastic scintillators have a poor resolution, so they cannot identify the material originating the radiation.

# Types of alarm



- **False alarms:**

  **alarms not triggered by the presence of any radioactive material inside the portal area (f.i. electronic noise)**

- **Innocent alarms:**

  **alarms produced by the justified presence of radioactive materials**
  - **Naturally Occurring Radioactive Material**
  - **Medical isotopes**
  - **Legal shipments of radioactive sources**

- **Real alarms:**

  **alarms produced by the unexpected (illegal?) presence of radioactive materials**

# Alarm rates



**False alarm can be reduced by technical means.**

**IAEA recommends in technical specifications a requirement of false alarm rate <1/10000 events.**

**Innocent alarms depend on the frequency of NORM content in ordinary shipment or treated people in normal population.**

**Recent statistics report that approximately 1 to 2% of transits trigger an innocent alarm:**

**- several tens trucks per day in a border crossing station**

**- hundreds of containers per day in a port**

**needing secondary inspection**

# Innocent alarm rate



| Alarms* | Reason | Max. observed multiple of background |
|---|---|---|
| 10 per day | Industrial Products and Raw Material e.g. ceramics, fertiliser, lamps, TV, etc | 10 / some events with e.g. ceramics |
| 1 per week | Agricultural Products e.g. fruits, vegetable, wood, etc. | 5 / e.g. one event with a chicken transport |
| 1 per week | Iron and Metal Transports e.g. Scrap, etc. | 50 / e.g. contaminated metal plates |
| 1 per week | ADR (legal) Transport of Radionuclides e.g. radio pharmaceuticals and industrial sources, etc. | 60 / almost all legal transports |

* Traffic approximately 1000 trucks per day

Table 1: Categories of goods which triggered alarms at the ITRAP truck lane during an observation period of 6 months (totally about 200000 trucks)

**Data source:**

WORLD CUSTOMS EXHIBITION AND FORUM, Budapest, 22-24th September 2003

**The Application of Gamma Spectrometric Techniques with Plastic Scintillators for the Suppression of "Innocent Alarms" in Border Monitoring for Nuclear and other Radioactive Materials**

K. E. Duftschmid, Technical University Graz, Austria

# Innocent alarm rate



| **Month** | **Port of Antwerp** | | |
|---|---|---|---|
| | **Alarms/day** | **Occupancies /day (truck)** | **Alarm rate** |
| Jan | 108 | 10232 | 1.1% |
| Feb | 118 | 10811 | 1.1% |
| Mar | 148 | 11374 | 1.3% |
| Apr | 144 | 11062 | 1.3% |
| May | 165 | 13271 | 1.2% |
| Jun | 156 | 11887 | 1.3% |
| Jul | 195 | 14187 | 1.4% |
| Aug | ***206*** | 15260 | 1.4% |

# NORM's

| | K40 | Th232 | U238 | Ra226 |
|---|---|---|---|---|
| **FOODS** | | | | |
| Brazil Nuts | 100-500 Bq/kg | 0 Bq/kg | 0 Bq/kg | 0-100 Bq/kg |
| Salt Substitute | >1500 Bq/kg | 0 Bq/kg | 0 Bq/kg | 0 Bq/kg |
| Banana | 100-500 Bq/kg | 0 Bq/kg | 0 Bq/kg | 0-100 Bq/kg |
| Coffee | 500-1000 Bq/kg | 0 Bq/kg | 0 Bq/kg | 0 Bq/kg |
| Cereals | 100-500 Bq/kg | 0 Bq/kg | 0 Bq/kg | 0 Bq/kg |
| **MATERIALS** | | | | |
| Granite | 1000-1500 Bq/kg | 100-500 Bq/kg | 0 Bq/kg | 100-500 Bq/kg |
| Sand | 100-500 Bq/kg | 0-100 Bq/kg | 0-100 Bq/kg | 0-100 Bq/kg |
| Gravel | 100-500 Bq/kg | 0-100 Bq/kg | 0 Bq/kg | 0-100 Bq/kg |
| Limestone | 100-500 Bq/kg | 0-100 Bq/kg | 0-100 Bq/kg | 0-100 Bq/kg |
| Concrete | 500-1000 Bq/kg | 100-500 Bq/kg | 0 Bq/kg | 100-500 Bq/kg |
| Marble | 100-500 Bq/kg | 0-100 Bq/kg | 0-100 Bq/kg | 0-100 Bq/kg |
| Cement | 100-500 Bq/kg | 100-500 Bq/kg | 0 Bq/kg | 100-500 Bq/kg |
| Brick | 500-1000 Bq/kg | 100-500 Bq/kg | 0 Bq/kg | 500-1000 Bq/kg |
| Clinker | 500-1000 Bq/kg | 0-100 Bq/kg | 0 Bq/kg | 100-500 Bq/kg |
| Coal fly ash | 100-500 Bq/kg | 0-100 Bq/kg | 0 Bq/kg | 100-500 Bq/kg |
| Asbestos | 100-500 Bq/kg | 0-100 Bq/kg | 0-100 Bq/kg | 0-100 Bq/kg |
| Natural Gypsum | 100-500 Bq/kg | 0-100 Bq/kg | 0-100 Bq/kg | 0-100 Bq/kg |
| Pearlite | 1000-1500 Bq/kg | 0-100 Bq/kg | 0-100 Bq/kg | 0-100 Bq/kg |
| **CERAMIC INDUSTRY** | | | | |
| Ceramic raw materials | 500-1000 Bq/kg | 0-100 Bq/kg | 0-100 Bq/kg | 0 Bq/kg |
| Ceramic Sludges | 100-500 Bq/kg | 0-100 Bq/kg | 100-500 Bq/kg | 0 Bq/kg |
| Zircon sands | 0 Bq/kg | 500-1000 Bq/kg | >1500 Bq/kg | 0 Bq/kg |
| White porcelain stoneware | 500-1000 Bq/kg | 0-100 Bq/kg | 100-500 Bq/kg | 0 Bq/kg |
| Ceramic tiles | 500-1000 Bq/kg | 0-100 Bq/kg | 0-100 Bq/kg | 0 Bq/kg |
| **FERTILIZERS** | | | | |
| Phosphoric acid | 0 Bq/kg | 0 Bq/kg | 1000-1500 Bq/kg | 100-500 Bq/kg |
| Normal superphosphate | 0-100 Bq/kg | 0-100 Bq/kg | 500-1000 Bq/kg | 100-500 Bq/kg |
| Triple superphosphate | 0-100 Bq/kg | 0-100 Bq/kg | 1000-1500 Bq/kg | 100-500 Bq/kg |
| Mono ammonium phosphate | 0-100 Bq/kg | 0-100 Bq/kg | >1500 Bq/kg | 0-100 Bq/kg |
| Di-ammonium phosphate | 0-100 Bq/kg | 0-100 Bq/kg | >1500 Bq/kg | 100-500 Bq/kg |
| Di-calcium phosphate | 0-100 Bq/kg | 0-100 Bq/kg | 0 Bq/kg | 500-1000 Bq/kg |
| NPK (nitrogen/phosphate/potassium) | 0-100 Bq/kg | 0-100 Bq/kg | 100-500 Bq/kg | 100-500 Bq/kg |
| PK (phosphate/potassium) | 0-100 Bq/kg | 0-100 Bq/kg | 100-500 Bq/kg | 100-500 Bq/kg |
| Phosphogypsum | 0 Bq/kg | 0-100 Bq/kg | 0-100 Bq/kg | 100-500 Bq/kg |
| **COMMERCIAL ITEMS** | | | | |
| Gas Lantern Mantle | 0 Bq/kg | 500-1000 Bq/kg | 0 Bq/kg | 0 Bq/kg |
| Tobacco | 0 Bq/kg | 0 Bq/kg | 0 Bq/kg | 0-100 Bq/kg |
| Kitty Litter | 100-500 Bq/kg | 0-100 Bq/kg | 100-500 Bq/kg | 0 Bq/kg |
| Glossy paper (kaolin) | 0 Bq/kg | 0-100 Bq/kg | 0-100 Bq/kg | 0 Bq/kg |
| Glazed Ceramics Surfaces | 0 Bq/kg | 500-1000 Bq/kg | 500-1000 Bq/kg | 0 Bq/kg |
| NBS Glass | 0 Bq/kg | >1500 Bq/kg | 0 Bq/kg | 0 Bq/kg |

**LEGEND**

| | |
|---|---|
| white | 0 Bq/kg |
| light yellow | 0-100 Bq/kg |
| yellow | 100-500 Bq/kg |
| orange | 500-1000 Bq/kg |
| red-orange | 1000-1500 Bq/kg |
| brown | >1500 Bq/kg |

# Medical/industrial isotopes



| | Am241 | Ba133 | Cs137 | Co57 | Co60 | Ga67 | I131 | In111 | Ir192 | Tc99m | Ti201 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **HELTH & MEDECINE** | | | | | | | | | | | |
| Medical Isotopes | | | X | X | | X | X | X | | X | X |
| Brachytherapy | | | X | | X | | X | X | | | |
| **INDUSTRIAL ITEMS** | | | | | | | | | | | |
| Smoke Detector | X | | | | | | | | | | |
| Fluorescent Lamp starter | | | | | X | | | | | | |
| Electronic Equipment | | X | | | | | | | | | |
| Voltage Regulator | | | X | | | | | | | | |
| Thickness Gauging Device | | | X | | | | | | | | |
| Glow Lamp | | | | | X | | | | | | |
| Moisture Density Gauge | X | | X | | | | | | | | |
| Radiography Camera | | | | | | | | | X | | |
| Gamma Radiography | | | | | X | | | X | | | |

# Innocent alarm rate

**Consequence of too high alarm rates:**

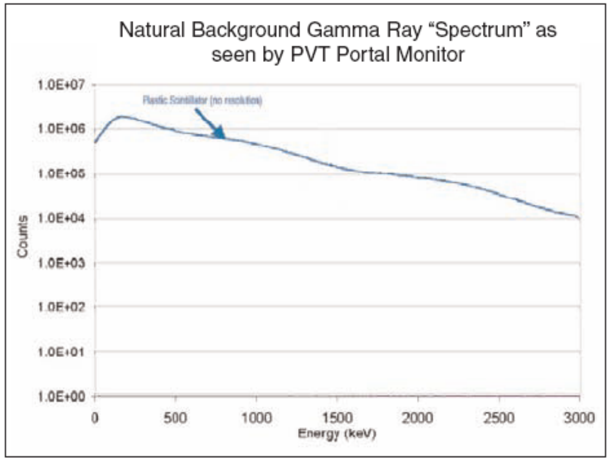
- **Overwhelming operational effort to be devoted to secondary inspections by FLO’s**
- **Inurement: FLO’s gets used to see them and lower their attention level**

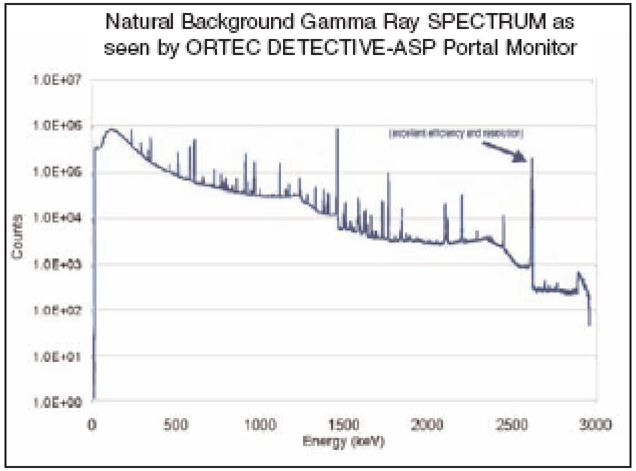
**Need to tackle seriously the problem of alarm reduction**

# How to reduce innocent alarms ?



- **Secondary screening** to determine the specific source of alarming events could be done using a **spectroscopic portal monitor** of comparable detection sensitivity than PVT
  - But their cost is very high!
    (to purchase, to use & to maintain)




- **Spectral energy discrimination** could be used to control the nuisance alarm
  - Expertise required!

# How to reduce innocent alarms ?



- Discrimination between **NORMs** **&** **SNM** **&** **Radioactive sources** is not straightforward. The **poor energy resolution** of the RPM does not allow isotope identification, and its response is poorly correlated in energy.

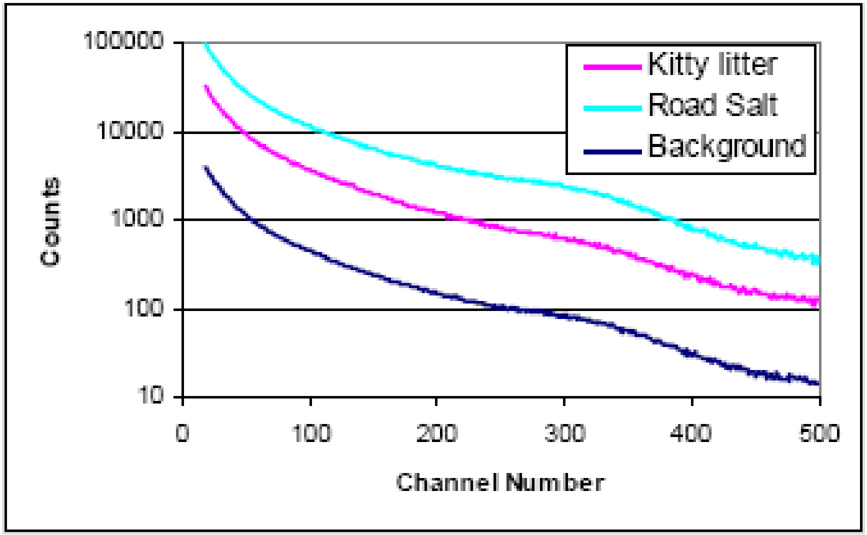
- But if PVT distorts the incident spectra, there are subtle variations in the energy response that allow spectral analysis by selecting a few broad energy windows. Discrimination between these 3 categories can be made via a broad energy windowing:
  - **Low energy window** = medical and SNM
  - **Medium energy window** = industrial isotopes
  - **High energy window** = NORMs

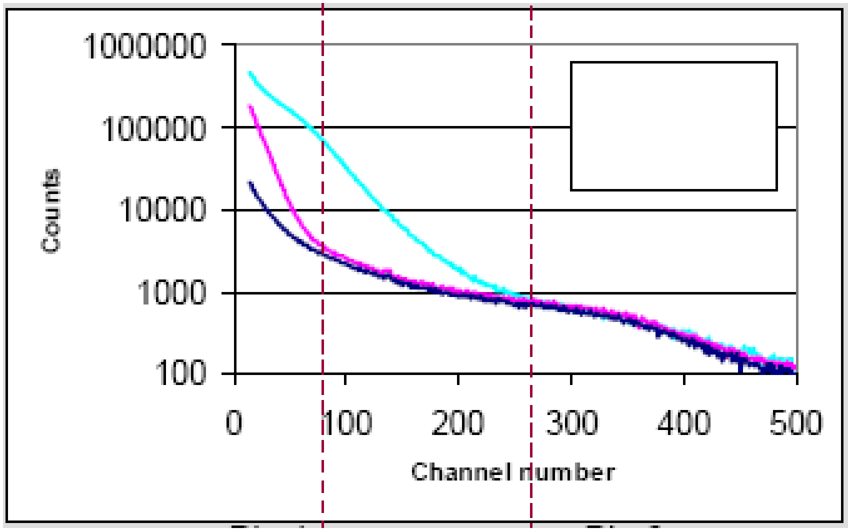
- Another way of discriminating NORMs would be to do a **secondary screening** to determine the specific source of alarming events. This could be done using a **NaI or a HPGe portal monitor** of comparable detection sensitivity than PVT.

# Broad Energy Windowing Method

NORMs

SNM



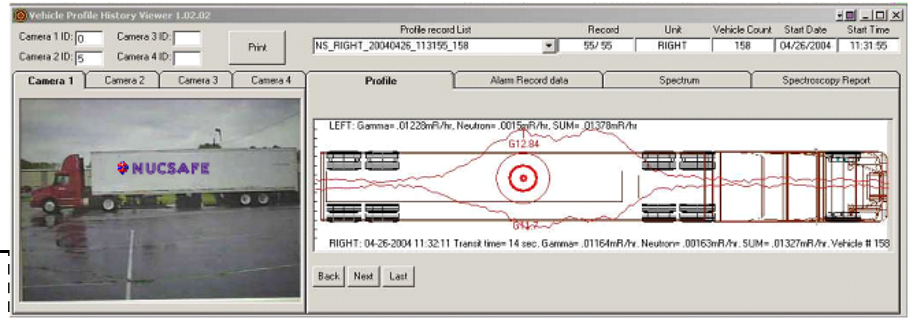



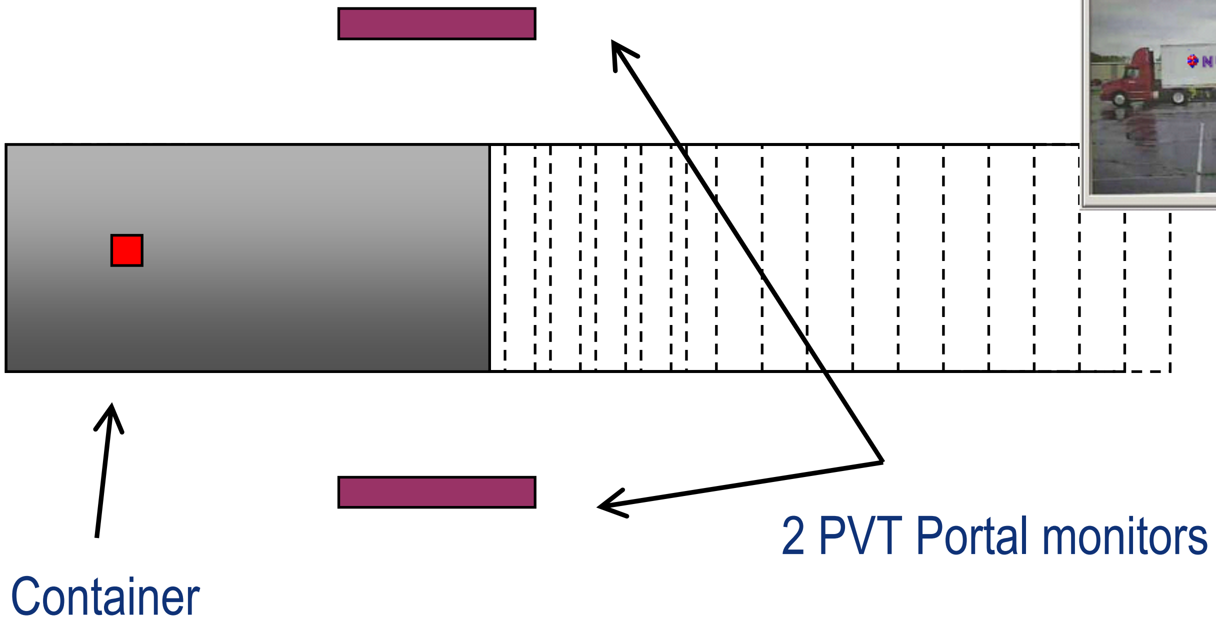

“Spies, lies and nuclear threat”, J.Ely & R.Kouzes, HPS, July 2005 meeting

- **If the alarm threshold of the total count rate is exceeded, the total counts are compared to the counts in the three energy windows**
  - **SNM will only trigger an alarm in the low energy window**,
  - **Industrial isotopes will trigger in the low & medium energy windows**
  - **NORMs will trigger an alarm in all the 3 energy windows (increase of the background level but the shape is the same)**

# Discrimination with Spatial Distribution



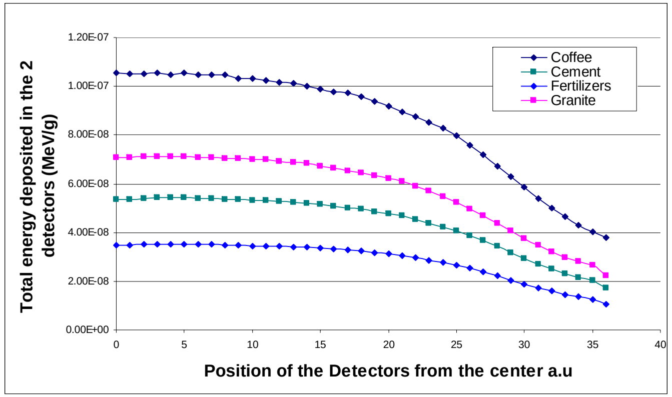


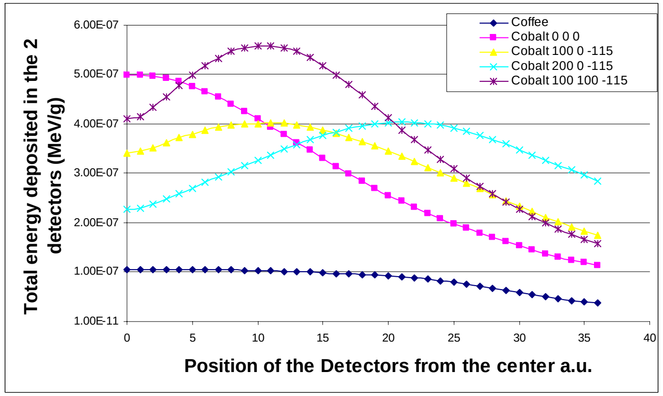

The total energy deposited in the portal monitors is calculated for each position of the truck moving forward

When containing **NORMs** the container is **homogeneously distributed**

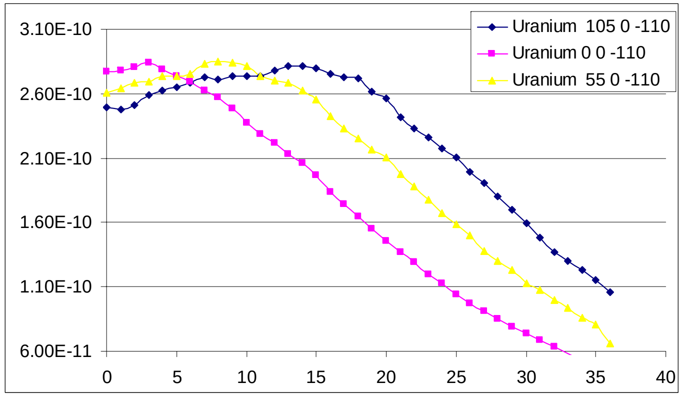
When containing **SNM or a radioactive source**, the material is **locally positioned**




NORM




1.7 g of Co-60




25 kg of HEU

- A **small radioactive source** will lead to a **narrow peak** of the detector response, while a homogeneous **NORM** container will lead to a **broader distribution**
- The full width at half maximum **(FWHM)** of the fitted gaussian will discriminate the distributed NORMs from the small and localized sources
- The space distribution will be obtained by coupling the time evolution of the detector response with a **truck speed detector**

# Information analysis



**Information analysis can help to improve the situation**

**For instance if:**

- **Shipper declaration states a material typically containing NORM**
- **Broad energy windowing shows homogeneous increase in the spectrum**
- **Spatial profile confirms broad distribution**

**=> then the material can be trusted to be NORM**

**There is much more information available than simple radiation level**

# Spectroscopic portal monitors





## Spectroscopic portal monitors

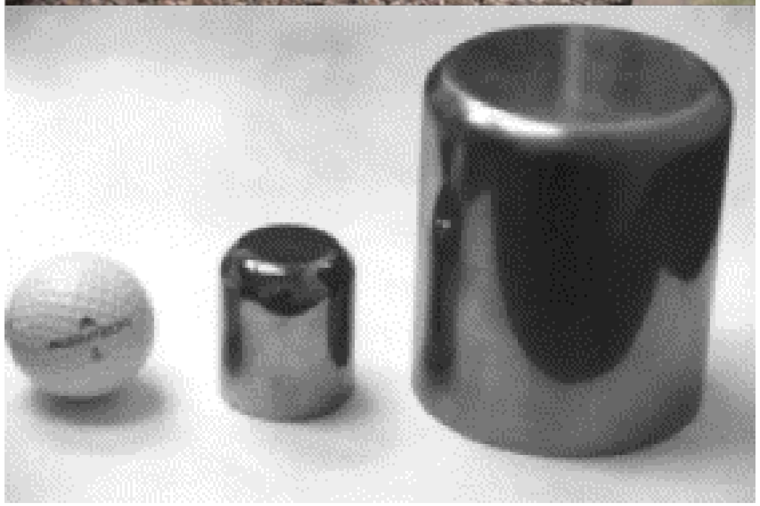
- new generation of portal monitors under development
- combination of detection and nuclide identification provides the possibility to immediately identify NORM, medical as well as legal radioisotopes and to dramatically reduce innocent alarms
- complex system of detection modules and sophisticated software requires extensive testing
- can be applied in principle for trains, trucks, cargo, pedestrians
- spectroscopic portals provide an interesting option for future installations, however, they have higher resource requirements

- High resolution
- High sensitivity (results in a short time)
- Require cooling to low temperatures (LN2)
- High price
- Complexity of data treatment

# Spectroscopic portal monitors



- Portal monitors have to cover a certain height for an efficient detection
- For constructional reasons, HPGe (and CZT) detectors cannot be produced in larger dimensions
- Largest HPGe detector[1]:
  - Ø 98 mm, length 110 mm
  - volume 110 $cm^3$, weight ≈ 4.4kg
  - at 3700 V operating voltage FWHM at 1.33 MeV: 2.4 keV

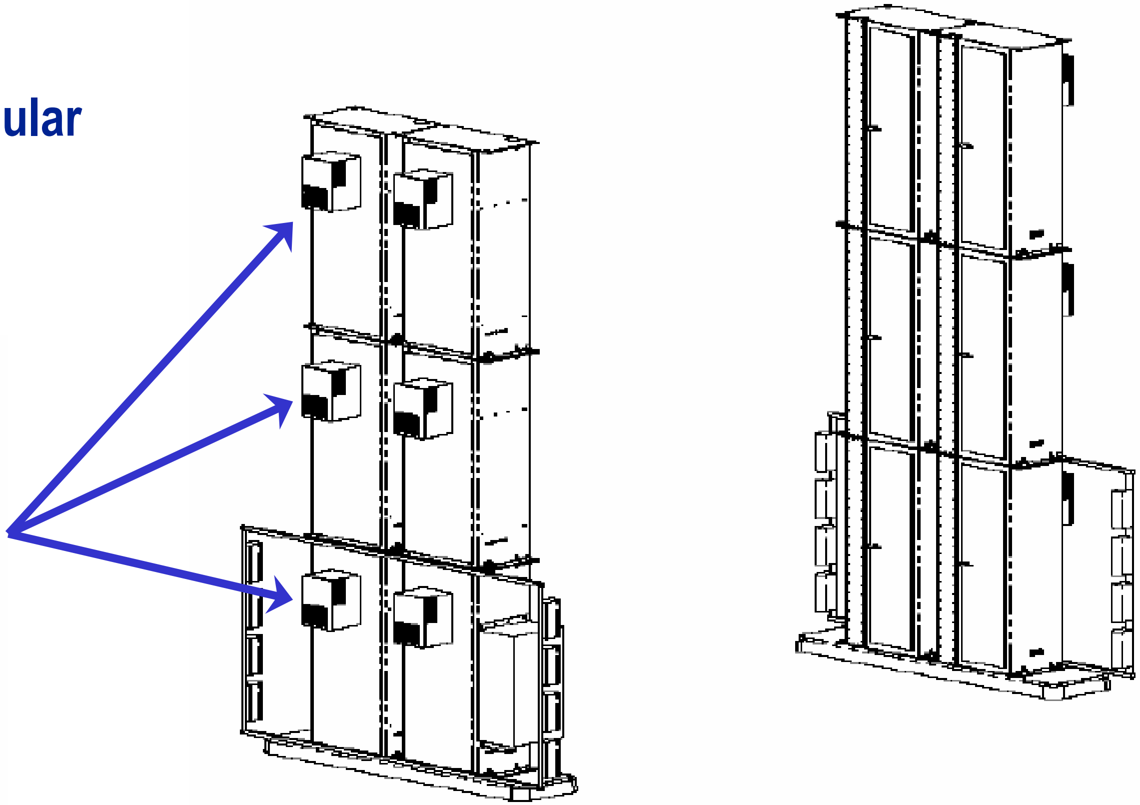
A portal monitor with one huge HPGe crystal cannot be achieved.

[1]Pat Sangsingkeow, Kevin D. Berry, Edward J. Dumas, Thomas W. Raudorf and Teresa A. Underwood, Advances in germanium detector technology, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Vol. 505, Issues 1-2, Proceedings of the tenth Symposium on Radiation Measurements and Applications, 1 June 2003, Pages 183-186. (http://www.sciencedirect.com/science/article/B6TJM-486229H-S/2/3b44eddbf14af13117b8a8d69947263c)

# Spectroscopic portal monitors



**Spectroscopic portal monitors can be constructed by combining several modular HPGe detectors**



Modular electrically cooled HPGe detector with built-in ADC and USB connection (Ortec)

- Self-contained subsystem, comprising a single, electrically cooled HPGe detector of standardized crystal dimensions and all necessary electronics.
- Detects gamma rays and sends the energy histogram or digitized pulse stream directly to a PC for analysis.

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# Portable equipment

ipsc
Institute for the Protection and Security of the Citizen



**From technological point of view is OK:**
- portable radiometers,
- isotope identifiers
- high-resolution spectrometers based on TD-cooled HPGe
- personal dosimeters (pagers)


**Special attention to be paid to:**
- ergonomic
- portability
- user-friendliness

**Instruments to be used by non-experts:**
- few (no) settings
- few simple options
- fully automatic data analysis
- clear messages

# Radiation protection issues





## Health and safety is paramount when responding to radiation detection alarm

- The personal radiation detector (PRD) maintains safety while officer responds to alarm
- PRD provides immediate indication of exposure to elevated radiation (vibration/acoustic alarm)
  - many PRD's sensitive to gamma radiation only
  - some are also neutron sensitive
  - (new) recently some models have spectroscopic capabilities (SPRD)

| Model/Manufacturer | Detector Type | Indicators |
|---|---|---|
| Radiation Pager<br>Sensory Technology Engineering, Inc. | Cesium Iodide scintillation detector (gamma only) | Radiation intensity indicated by modulated audio tone and daylight visible LED |
| PM1703MO-1<br>Polimaster | Small-sized GM tube and highly sensitive CsI(Tl) scintillation detector | Dose and dose rate of gamma radiation |
| EPD Mk2<br>Thermo Scientific | Multiple diode-based detector (gamma, X-ray and beta) | Dosimeter for detecting and monitoring radiation exposure |

# Localisation



- **Survey meter is the primary search device to determine whether radiation is uniformly distributed or localized. Depending on the specific equipment model, a survey meter is sensitive to gamma only, neutron only or both gamma and neutron radiation**
  - **It is more sensitive than PRD in detecting radiation**
  - **It is more sensitive to gross radiation counts than the more expensive radioactive isotope identifier device (RIID).**

PRM-470C/G/N/GN
(gamma, neutron, gamma-neutron hand held detectors)
TSA

Neutron detector

FH 40 G/GL
Dose Rate (gamma)
Thermo Scientific

# Identification



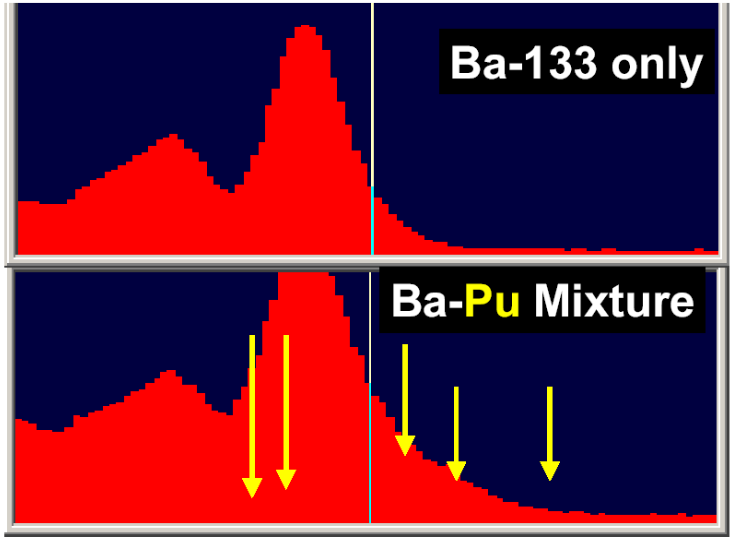
- **The handheld gamma spectrometer (radioactive isotope identification device – RIID) is sensitive, more advanced instrument designed for accurate categorization of radioactive materials.**
  - **Gamma spectrometers employ NaI(Tl) scintillator, HPGe or CdZnTe technologies to provide nuclide identification**
  - **Isotope identification can be challenging for low level radiation such as that typically encountered with Naturally Occurring Radioactive Materials (NORM)**



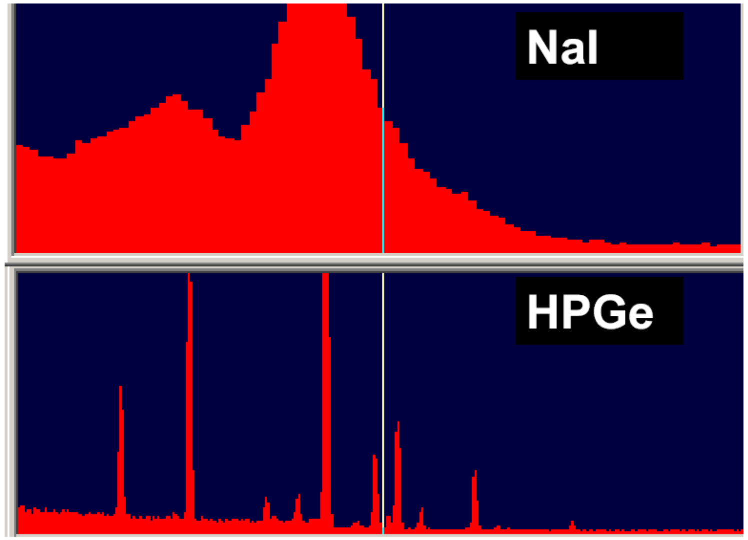
# Fissile hidden in declared RM



***NaI Detector** (arrows indicate undetected Pu peaks)*




**Weapons Grade Pu and Ba133 mixture**




**Spectroscopy can improve the capability to detect illegal material inside legal shipments of radioactive sources**

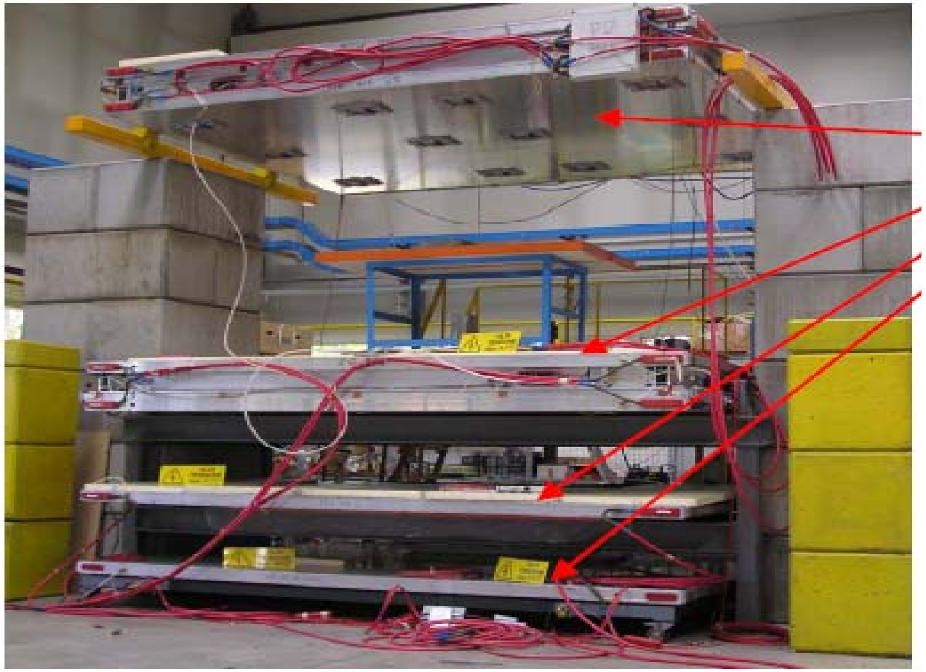
# Detection of shielded material



**Muon radiography to detect high-Z material:**
**- Direct detection of fissile material (U, Pu)**
**- Indirect detection of materials (Pb, W) used to shield RS/SNM**

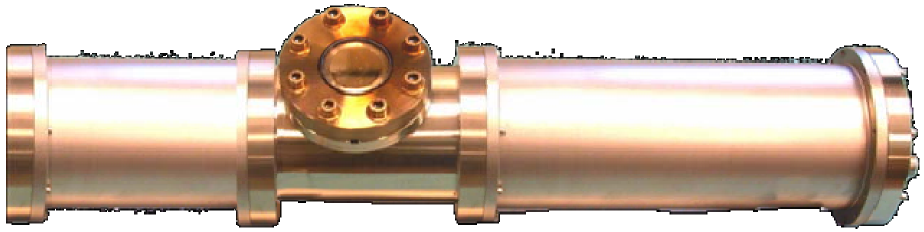
**Natural source of muons from cosmic radiation**
**Muons when passing through material are deflected with an angle that is proportional to Z**

**Placing position-sensitive detectors (drift-chambers) below and above the inspected object it is possible to evidence shadows produced by heavy materials with image reconstruction techniques**



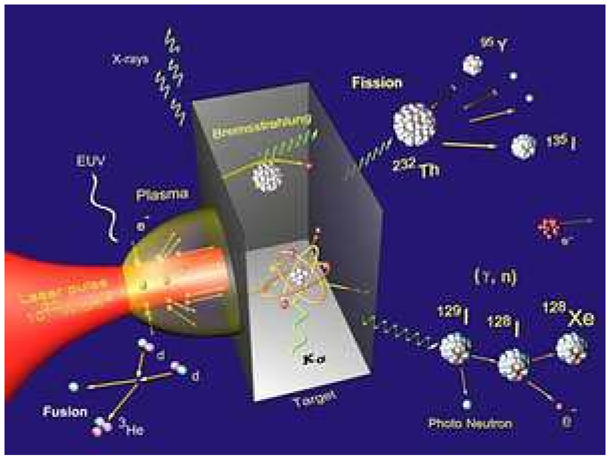
# Active methods

## Neutron interrogation



using (portable) generator tubes
Based on (D,T) or (D,D) reactions

## Photofission




using:
- electron accelerators + bremsstrahlung

or
- tabletop laser systems

# Conclusions

- There is no fit-all-purposes solution
  => techno-diversity
- Operational aspects have paramount importance
  lower alarm rate
  usability issues
- Combining multiple info by different sources/sensors
  smart/distributed sensors
  expert systems
- Potential novel technologies, but high-tech
  long term developments

# Thank you !

**For further information or questions please contact me**

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